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Technological Challenges in Thermal Plasma Production*

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Abstract

Thermal plasmas, generated by electric arc discharges, are used in a variety of industrial applications. The electric arc is a constricted electrical discharge with a high temperature in the range 6000–25,000 K. These characteristics are useful in plasma cutting, spraying, welding and specific areas of material processing. The thermal plasma technology is an enabling process technology and its status in the market depends upon its advantages over competing technologies. A few technological challenges to enhance the status of plasma technology are to improve the utilisation of the unique characteristics of the electric arc and to provide enhanced control of the process. In particular, new solutions are required for increasing the plasma–material interaction, controlling the electrode roots and controlling the thermal power generated by the arcing process.

1. Introduction

A thermal plasma is often considered as a plasma in which local thermodynamic equilibrium (LTE) conditions prevail. Under LTE conditions, the heavy particles in the plasma have approximately the same temperature as the electrons and hence the plasma has a high temperature. This allows the plasma to be used in a number of industrial processes requiring process heat at a high temperature (Pfender 1988). Typical applications of thermal plasmas in industry include joining of metals, plasma cutting, plasma spraying, arc wire spraying, plasma surfacing and material processing.

Thermal plasma technology is essentially a process technology that enables the development of an industrial process to manufacture a product that meets market demands. The success of an application of plasma technology in industry will depend upon the technical suitability and advantages the process offers and the cost of the final product.

Thermal plasma technology is based on the physical phenomenon of electrical discharges. The basic properties and generic features of the phenomenon create a unique position for the industrial applicability of the process. On the other hand, the limitations and the constraints imposed by the phenomenon on the application process have a strong bearing on the total cost and hence on the acceptance of the process by industry. In this paper, the advantages of plasma technology, its phenomenal constraints and future challenges for technology developments are highlighted.

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2. Thermal Plasma Applications

In many industrial applications, a thermal plasma is generated by an electrical discharge in a gas. Most of the industrial applications of today use an electrical discharge with electrodes to create a hot plasma. At pressures of ~1 atm and current levels of >100 A, such discharges (Maecker 1964) tend to be high-pressure electric arc discharges.

The electric arc is sustained between two electrodes by the passage of an electric current. The electric arc phenomenon is characterised by a highly luminous and high-temperature plasma column, a highly constricted cathode attachment with a relatively low value of cathode fall voltage, and a diffuse anode attachment. The plasma column of an electric arc is that region of the arc plasma lying between the cathode and anode boundary layers. The electric field within the plasma column is relatively small and quasi-neutrality of charge exists in the column.

The high-pressure arc discharge has a temperature in the range 6000–25,000 K and a power density of 10^3–10^6 W cm^{-3} depending upon the gas composition, discharge current, gas pressure, gas flow and the plasma confinement. Such high temperatures and power densities, attainable with considerable ease, make the arc-generated plasma particularly unique and attractive for certain industrial applications (Ramakrishnan 1991).

Electric arcs are used in two different modes in industrial devices, namely the non-transferred arc or the transferred arc (see Fig. 1). In a non-transferred plasma system, an electric arc is maintained in a plasma torch or heater through which a gas of suitable composition is passed to be heated by the electric arc; the gas heated by the arc emanates from the torch as plasma gas, which in turn is used for a given process. Typical applications of this type of plasma generation

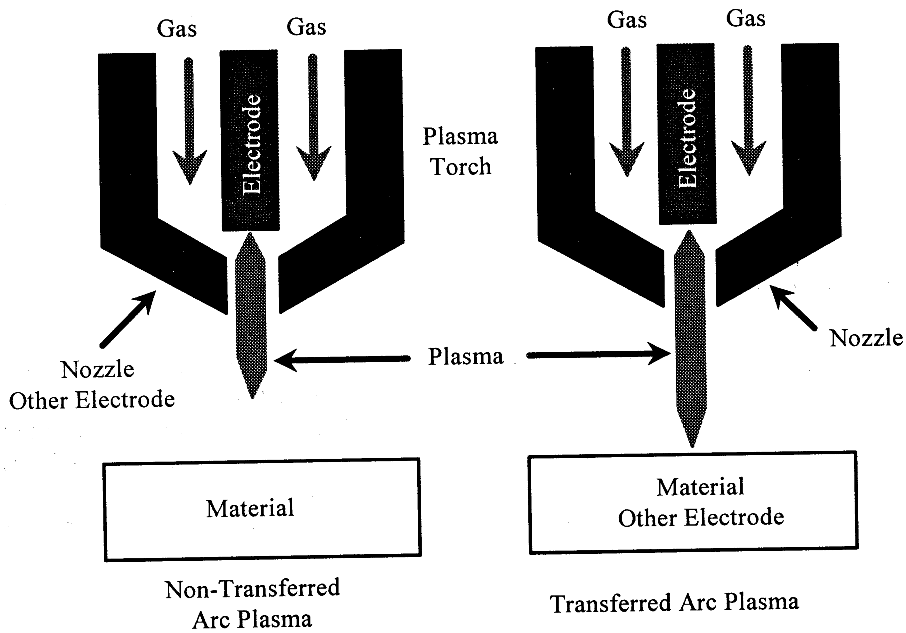

Fig. 1. Transferred and non-transferred plasmas.

are material processing using plasma heaters (Fig. 2*a*), in-flight processing of material and plasma spraying (Fig. 2*c*).

In a transferred arc system, an arc is generated between an electrode, which may be located within a plasma torch, and the material being processed. The material being processed needs to be electrically conducting (usually metallic)

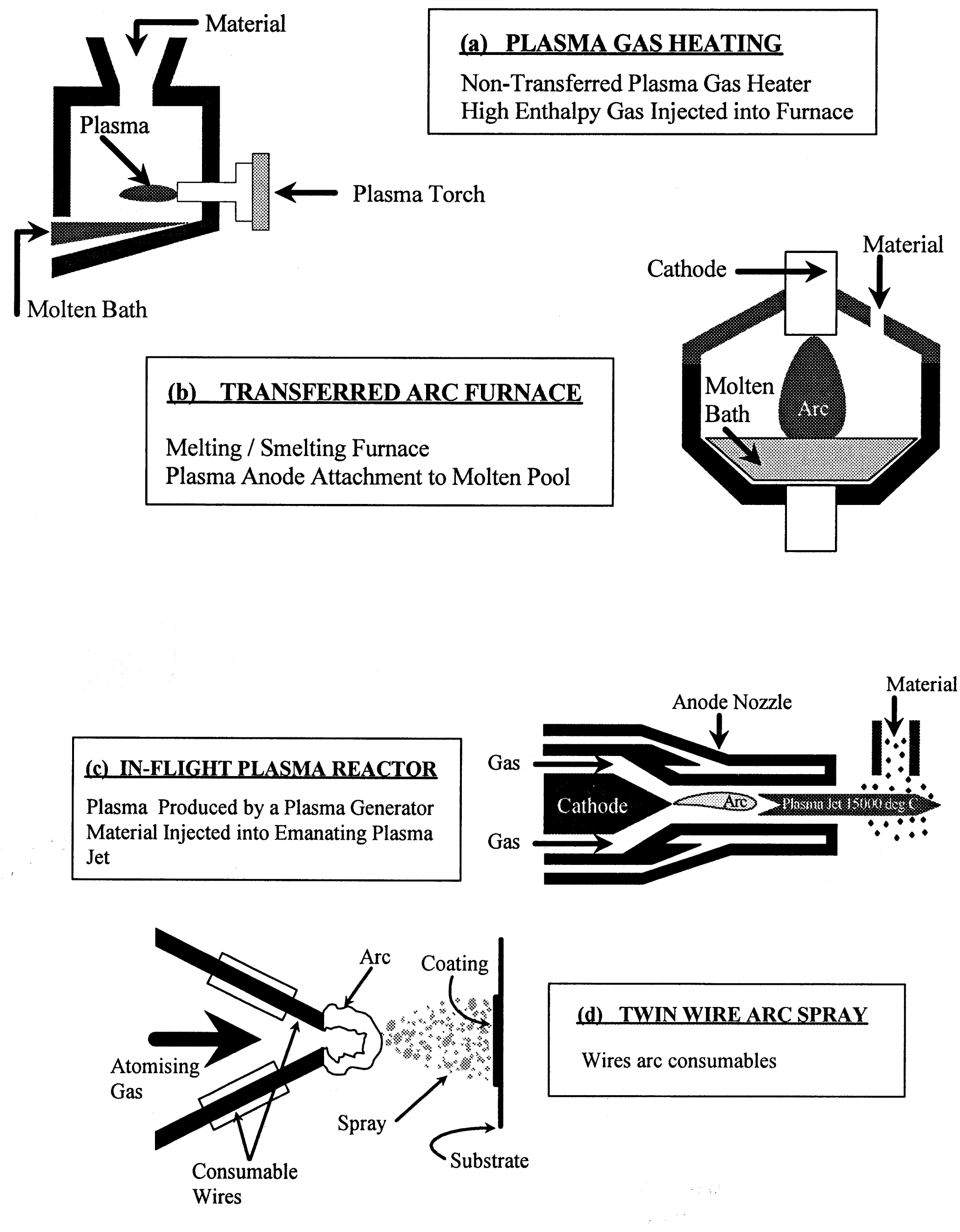

Fig. 2. Configurations of plasma/arc processors.

because it serves as one of the electrodes of the arc. Transferred arc mode of operation is used in arc furnaces (Fig. 2*b*) for special steel making, plasma cutting, plasma welding and plasma transferred arc surfacing.

The two terms *arc* processing and *plasma* processing are also used in industry. The processes representing the *arc* processing category are *arc welding* and *arc wire spraying* (Fig. 2*d*). In these processes, the electric arc is directly involved in the process and most often one or both of the electrodes of the arc are consumable. On the other hand, *plasma* processing systems are the same as non-transferred systems, the exceptions being *plasma* transferred-arc surfacing and *plasma* welding.

3. The Electric Arc Phenomenon

From a scientific point of view, studies aimed at understanding the behaviour of the plasma column and the electrode roots of an electric arc are important. A large number of studies (Jones and Fang 1980; Finkelnburg and Maecker 1956) on these aspects have been undertaken in the past. These studies highlight the phenomenal features and constraints associated with an electric arc.

3·1 Plasma Column

3·1·1 Plasma Temperature and Column Size

The temperature attainable in a plasma column and the size of the column are characteristic features of an electric arc and have a strong bearing on the applicability of the phenomenon in industrial processes. Measurements and calculations of temperatures of arc columns in various configurations have been performed by a number of researchers (Maecker 1964; Jones and Fang 1980).

A simple configuration of a plasma, which gives a good insight into the properties of an arc column, is a cylindrically symmetric column. In a cylindrical plasma column, the electrical power input is transported radially by thermal conduction and radiation, as given by

$$\frac{1}{r}\frac{\mathrm{d}}{\mathrm{d}r}\left(r\kappa\frac{\mathrm{d}T}{\mathrm{d}r}\right) - u + \sigma E^2 = 0\,, \tag{1}$$

where r is the radial coordinate, T the temperature and E the axial electric field. The transport properties of the plasma are κ, the thermal conductivity, σ, the electrical conductivity, and u, the net radiation emission from the net plasma. The plasma being current maintained, Ohm's law is obeyed:

$$I = \int_0^R E\sigma 2\pi r\,\mathrm{d}r\,, \tag{2}$$

where I is the total arc current and R is the radius of the arc column.

The thermal and electrical conductivities of thermal plasmas are strong functions of plasma temperature as shown in Fig. 3. For example, the electrical conductivity σ varies by three decades in the temperature range 5000–25,000 K.

The temperature distribution in the arc column can be calculated for a given arc current I by solving equations (1) and (2) for a given set of boundary conditions, which may be of the form

$$\left.\frac{\mathrm{d}T}{\mathrm{d}r}\right|_{r=0} = 0, \qquad T|_{r=R} = T_{\mathrm{w}}\,, \tag{3}$$

where T_{w} is the wall temperature at a radius R corresponding to the wall.

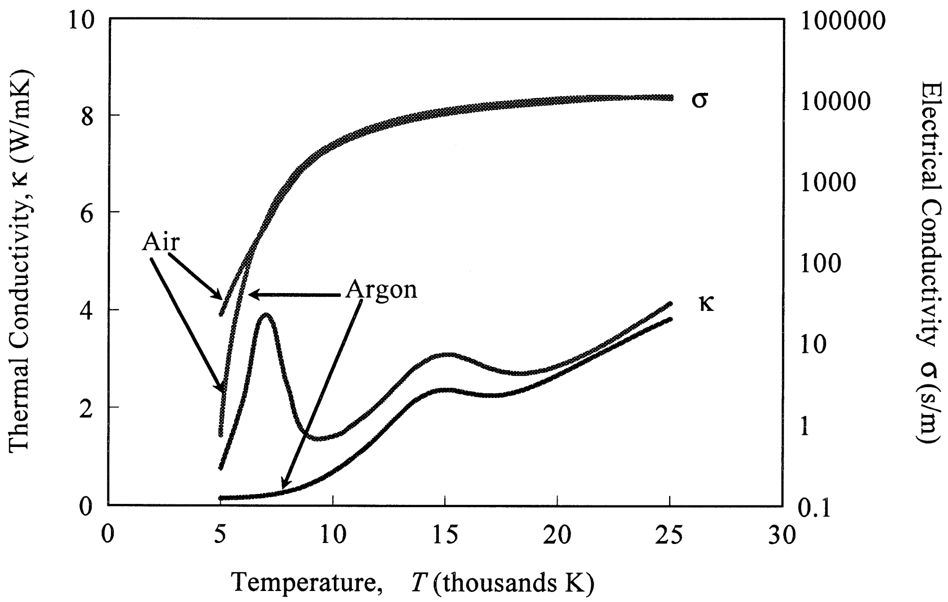

Fig. 3. Variation of electrical and thermal conductivities of plasmas with temperature.

The main feature of the discharge, viz. the size of the current-carrying region, can be illustrated by assuming that a discharge is initiated in a low-temperature plasma (Fig. 4) and the discharge current is increased gradually.

At low currents, the plasma temperature is $\sim$10,000 K and the radiation from the plasma can be neglected. Equation (1) can be transformed in terms of the Schmidt heat flux potential,

$$S = \int_{T_{\mathrm{ref}}}^{T} \kappa \,\mathrm{d}T\,,$$

which is a monotonically increasing function of temperature and thus represents the temperature of the plasma, to give

$$\frac{1}{r}\frac{\mathrm{d}}{\mathrm{d}r}\left(r\frac{\mathrm{d}S}{\mathrm{d}r}\right) + \sigma E^2 = 0\,, \tag{4}$$

with the boundary conditions

$$\left.\frac{\mathrm{d}S}{\mathrm{d}r}\right|_{r=0} = 0, \qquad S|_{r=R} = S_{\mathrm{w}}\,, \tag{5}$$

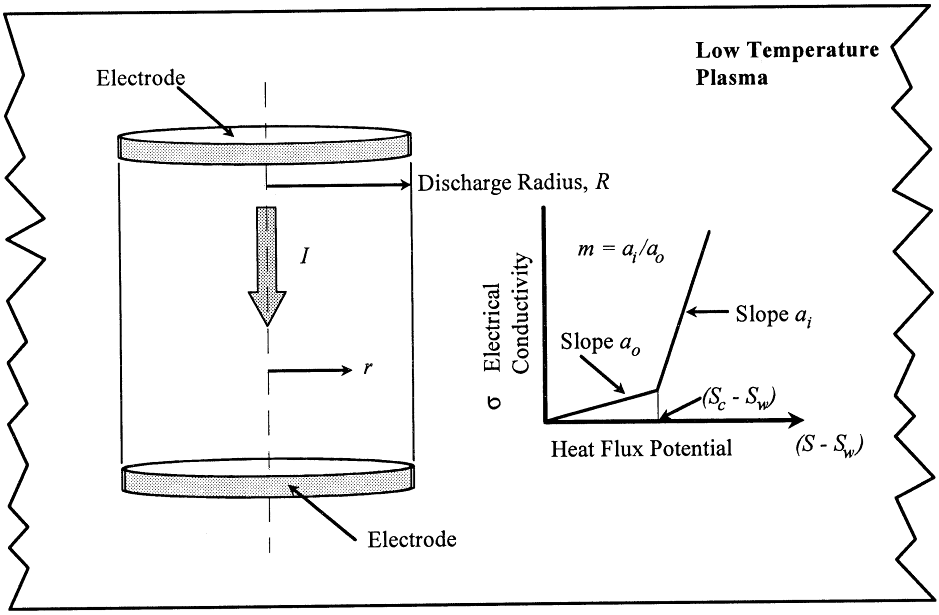

Fig. 4. Cylindrical arc discharge.

where S_w is the heat flux potential corresponding to the wall temperature T_w.

The dependence of the electrical conductivity σ on the heat flux potential can be approximated by the piecewise linear relationships

$$\begin{aligned}\sigma &= a_\mathrm{o}(S - S_\mathrm{w}), & S &\le (S_\mathrm{c} - S_\mathrm{w})\\ &= a_\mathrm{i}(S - S_\mathrm{w}) + b_\mathrm{i}, & S &> (S_\mathrm{c} - S_\mathrm{w}),\end{aligned} \tag{6}$$

where the subscripts o and i describe the outer (or lower temperature) and the inner (higher temperature) of the discharge column respectively.

Defining

$$m = a_\mathrm{i}/a_\mathrm{o}\,, \tag{7}$$

one can compare the rates of increase of electrical conductivity with heat flux potential (or temperature) in the inner and outer regions of the arc column. Equations (4)–(7) can be solved analytically in terms of Bessel functions for the radial distribution of S and the variation of electric field with current for different values of the parameter m.

Fig. 5a shows the variation of normalised electric field with normalised current for a typical value of $m = 100$. It can be seen that the electric field collapses when the current is increased above a certain value. Fig. 5b shows the radial profile of the normalised heat flux potential, $U = (S - S_\mathrm{w})/(S_\mathrm{c} - S_\mathrm{w})$, for two cases when the discharge current is increased by a small amount. It is interesting to note that the profile becomes narrow, indicating that most of the plasma current is carried by the narrow inner region of the arc column when the current is increased above a certain value.

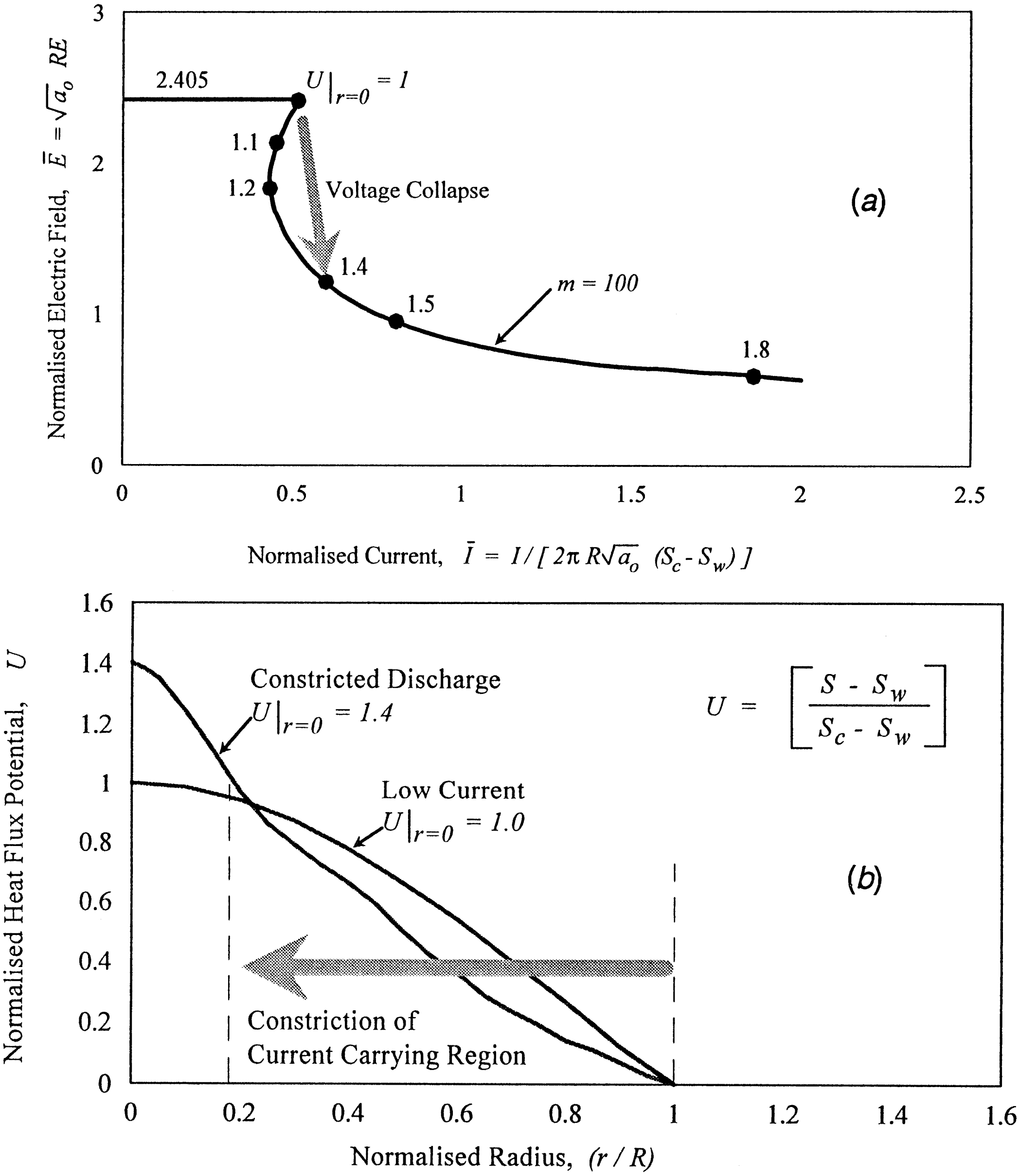

Fig. 5. Voltage collapse and constriction of a cylindrical arc discharge.

The above analysis shows that owing to a strong increase in electrical conductivity with temperature, when the discharge current is increased, the size of the discharge column and the electric field in the column collapse to small values. This phenomenon of the concentration of the discharge current in a narrow hot region of the plasma can be termed *electrothermal instability*, which is dependent upon the rate of increase of electrical conductivity with temperature, $d\sigma/dT$.

At high currents, the temperature of the plasma increases to values where radiation losses from the column become very dominant. The radiative processes in a plasma are extremely complex. An estimate of the radiative flux at any point in a plasma requires the integration of radiation flux over all frequencies and directions (Lowke 1970). For simplicity, the radiation loss in a plasma can be represented by the net radiation emission, the values of which are determined experimentally. In equation (1) the radiation loss from the arc column is represented approximately (Lowke and Ludwig 1975; Tuma and Lowke 1975) by the term u, which is the net radiation emission from the arc column. At the centre of the arc, the net radiation emission u is positive, while at the arc boundary u may be negative because strong reabsorption of radiation may take place at the boundary of an arc. The amount of radiation that leaves the arc is the transparent radiation u_t, which is a fraction of the net radiation u at the arc axis. Typically, the value of u_t is in the range $(0\cdot1\text{–}0\cdot3)u$.

The net radiation emission depends not only upon the plasma temperature, but also upon the temperature profile or the arc radius. Measurements have been made on wall-stabilised arcs to estimate the value of u for different tube radii. These estimates show that for tube radii of practical interest, the dependence of u on temperature is very strong. Hence, at fairly high arc currents or strong confinements, the value of u at $r = 0$ is very large compared with the thermal conduction at the axis of the arc. That is, at $r = 0$, $\sigma E^2 \approx u$, and the arc temperature is primarily determined by radiation. When the arc current is increased, the radiation loss at the arc axis increases significantly and hence the axial temperature increases only slightly. However, the radial temperature profile becomes flatter, because most of the radiated power from the axis is reabsorbed at the arc boundary. Fig. 6 shows the temperature profiles (Ernst *et al.* 1973) measured on a wall-stabilised arc column of tube of diameter $5\cdot0$ mm.

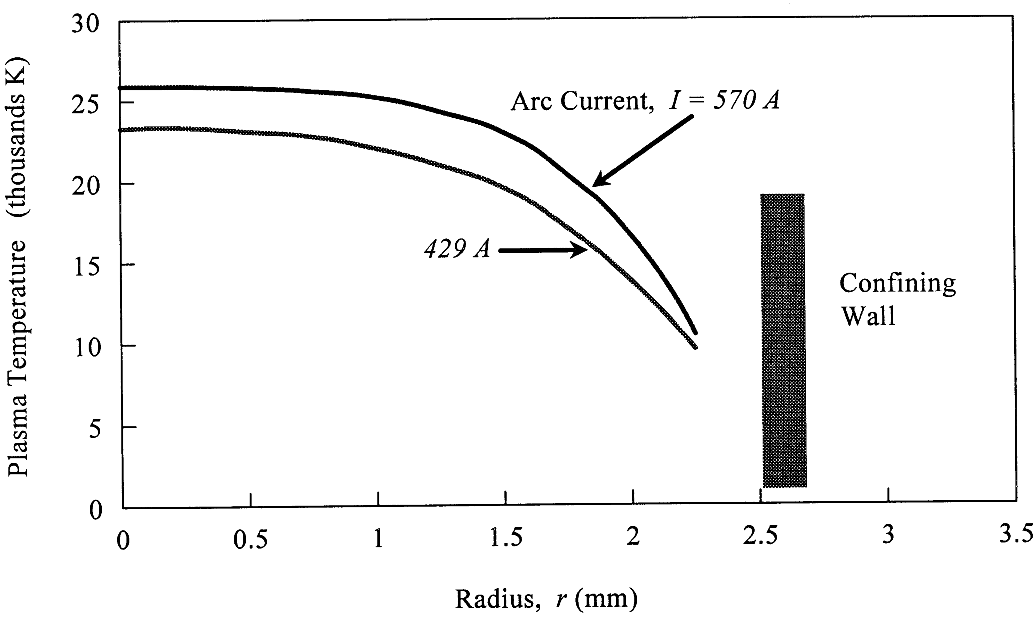

Fig. 6. Temperature profiles of wall-stabilised nitrogen arcs.

3·1·2 Plasma Column in Gas Flows

The plasma column of an electric arc represents that portion of the arc in which most of the heat for a given process is generated. Plasma generation for a process involves the entrainment of a suitable gas into an electric arc column wherein the entrained cold gas is heated by Joule heating within the column.

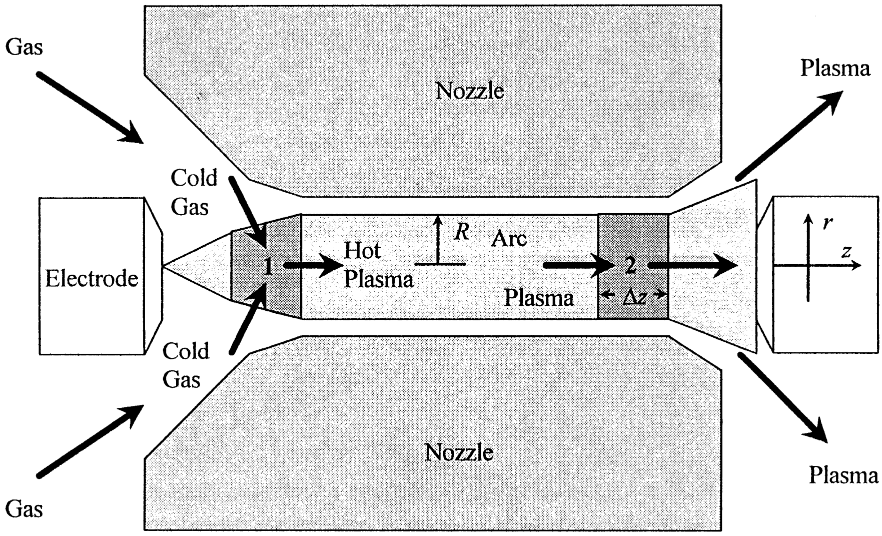

Fig. 7. An electric arc in forced convection.

The structure of an arc column in a typical plasma torch used for plasma generation is shown in Fig. 7. The arc column in the figure is represented by a boundary at radius R at which electrical conduction substantially reduces to zero. In the upstream end of the torch, cold gas is entrained into the arc column. If ρ, u_z, u_r and h are the density, axial velocity, radial velocity and enthalpy of the plasma gas at any radial (r) and axial (z) position, the total enthalpy of gas leaving any axial position is

$$\int_0^R \rho u_z h \, 2\pi r \, \mathrm{d}r$$

and the mass flow within the plasma column is

$$\int_0^R \rho u_z \, 2\pi r \, \mathrm{d}r \, .$$

The generation of plasma per unit length of the arc column is

$$q_c = \frac{\partial}{\partial_z}\left(\int_0^R \rho u_z h \, 2\pi r \, \mathrm{d}r\right)$$

and the amount of mass entrained into the column per unit axial length of the column is

$$m_r = \frac{\partial}{\partial z}\left(\int_0^R \rho u_z \, 2\pi r \, \mathrm{d}r\right).$$

That is,· the amount m_r entrained radially into the arc column in unit length of the column results in the generation of plasma with an enthalpy of q_c. If the electric field in the arc column is E at an arc current I, then the Joule heating per unit length $q_e = EI$. This amount of Joule heating is expended in generating a plasma with a total enthalpy of q_c and in the losses by radiation and thermal conduction processes to the wall of the plasma torch through the cold gas surrounding the plasma column.

Considerable work exists in the published literature which deals with the energy balance in an arc determined by convection, either forced or induced by arc pumping. These studies show that plasma generation takes place where there is a strong entrainment of cold gas into the arc column, as shown in upstream region 1 of the arc column of Fig. 7. When the plasma column is fully grown, as shown in downstream region 2 of the arc column in Fig. 7, the increase in the area of the arc column with axial distance is small. Consequently, the entrainment of cold gas into the column is small and very little extra plasma is generated. In the downstream region, the plasma column is nearly cylindrical and the electrical input is balanced by losses to the surroundings of the plasma column. Figs 8*a* and 8*b* show the calculated results (Ramakrishnan *et al.* 1978) obtained for a 2·16 kA free-burning arc, which is determined by strong convective flows driven by magnetic pumping. It can be seen that significant entrainment of cold gas takes place in the growth region of the plasma column and a large proportion of the Joule heating goes to generate plasma. In the fully developed downstream region, the proportion of the radiation losses from the plasma column is considerable and little extra plasma is generated.

3·2 Electrode Attachments

Analytical studies on the arcing phenomenon indicate that the interaction of the plasma with electrodes has still to be understood (Guile 1971). The region in front of an electrode (cathode or anode) is that portion of the discharge which contains the electrode surface, the space charge region immediately in front of the electrode and the transition zone to the plasma column. The region near the electrode is a boundary layer, where there exist very strong axial gradients in plasma properties such as the temperature, potential, particle densities, current density and radiation intensity.

At the cathode of an electric arc, electron emission takes place. The roles of different mechanisms for electron emission, whether thermionic or field emission, are yet to be understood. What is known is that when the cathode is thermionically emitting, the current density at the cathode (Morrow and Lowke 1993; Peiyuan *et al.* 1992) can be as high as $10^8\ \mathrm{A\,m^{-2}}$. When non-thermionic cathodes are used, the current density can be higher by two orders of magnitude; however, in order to prevent electrode melting, it is essential that the cathode root is moved rapidly over the electrode surface.

The anode region of an electric arc is characterised by an anode fall region to provide an electrical connection between the high-temperature plasma column and the cooler anode surface. The potential fall in the anode region enables

(Dinulescu and Pfender 1980) the production of ions in order to maintain the required ion flux in the plasma column towards the cathode, and the provision of appropriate potential for the collection of electrons. Observations suggest that the anode attachment is determined by the thermal conditions at the anode surface; if sufficient heat is provided by the plasma at the anode, the arc attachment at the anode is diffuse.

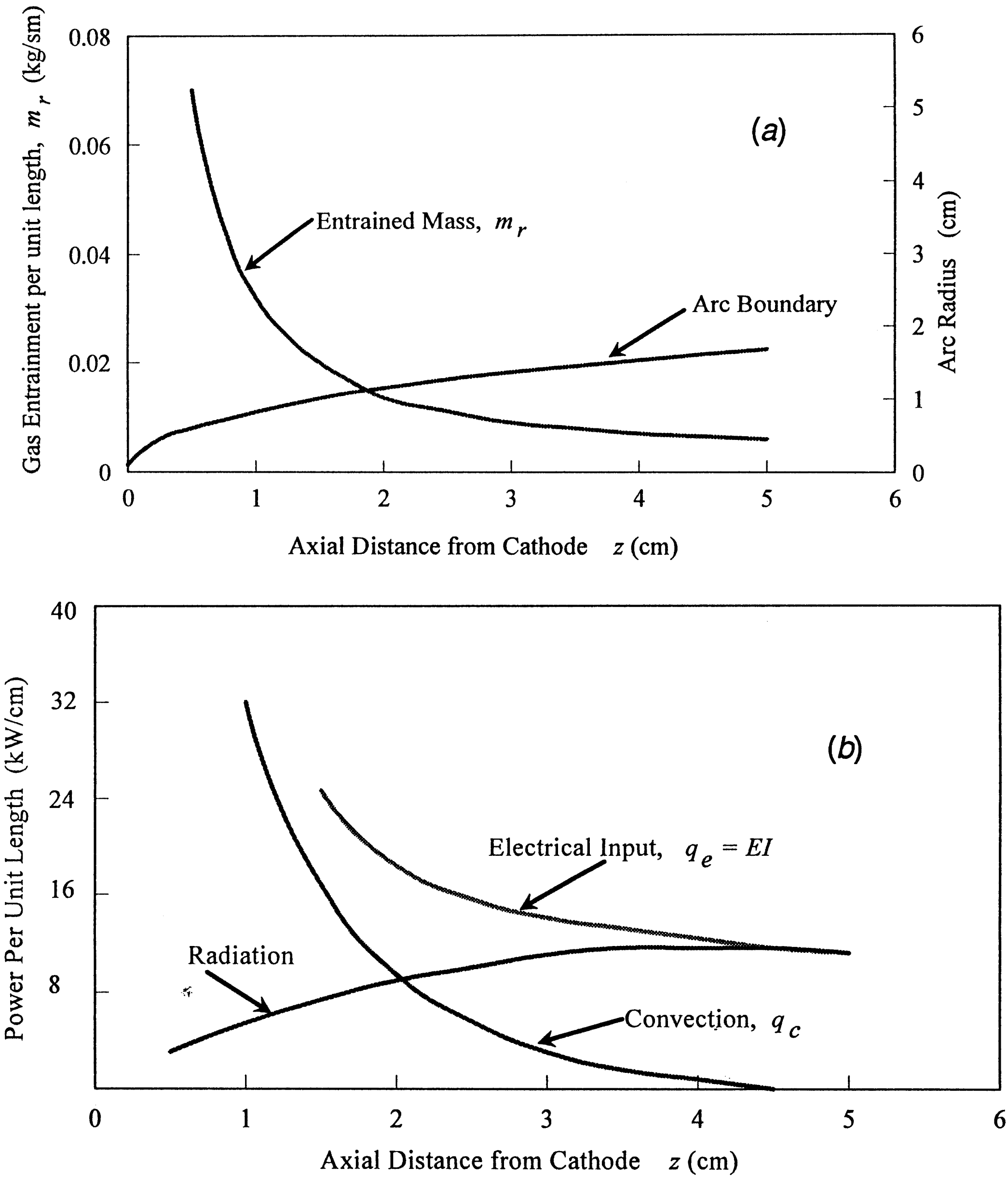

Fig. 8. Properties of a 2·16 kA free-burning arc in air with induced gas flows near the cathode.

Experimental studies aimed at understanding the behaviour of electrode attachments are hampered by extremely small sheath thicknesses of $\sim 0 \cdot 02$ mm and steep gradients in measurable properties. Recent calculations show that the energy processes at the cathode are: cooling by thermionic emission of electrons, ion heating and thermal conduction from the arc column. At the anode, the principal energy processes are thermal conduction from the arc column and the energy of the anode work function given up by the electrons. These calculations (Morrow and Lowke 1993) have been made for a free-burning arc in argon at a current of 200 A. When strong convective flows are encountered in the plasma, the heat transported to the electrode surface by convection needs to be taken into account in the energy flow estimates (Sanders and Pfender 1984). Experimental evidence obtained using free-burning arcs shows that more energy is liberated at the anode than at the cathode of an electric arc.

For the development of application-oriented technologies, the arc attachments at the electrodes are significant for their effects on (a) the heat flux on the electrode surface, (b) the rate of consumption or melting of the electrodes, and (c) the location of the electrode roots on the electrode surface.

Studies conducted so far do not give reasonable estimates of the heat flux at the electrodes. The mechanisms determining the location of electrode roots on electrodes are not known. This issue is particularly important in the design of plasma or arc systems and the control of the process.

3·3 Phenomenological Features

The two basic phenomenological features of the column of an electric arc are:

- the arc column is inherently narrow over a large range of arc currents, owing to the strong dependence of the electrical conductivity of the plasma on the plasma temperature, and
- the temperature of the arc column is high, typically in the range 5000–25,000 K, with steep temperature gradients in the radial direction at the arc boundary in most industrial plasmas.

The high energy densities and high temperatures in the plasma column, whose radial dimensions remain fairly small for a large range of currents, is advantageous in a few applications. For material processing, the required residence time in the plasma for the material to undergo chemical reactions is a very strong function of temperature. For example, the residence time required to decompose toluene to a level of 1 ppm falls from $3 \cdot 8$ ms at 2000 K to $0 \cdot 19$ ns at 12,000 K (Ramakrishnan and Deam 1993). From an engineering consideration, this feature is very attractive because for a given rate of throughput of material, the size of the reactor reduces, thus enabling the manufacture of compact hardware.

The narrow arc column is also useful when the melting of material in a small region is required. Plasma welding and plasma cutting are examples of techniques in which a narrow arc column is exploited to obtain a narrow heat-affected zone in welding or a narrow kerf in cutting.

It is known that the properties of the arc column are influenced by (i) the composition of the plasma gas (molecular gases tend to increase the enthalpy); (ii) the flow rate of plasma gas; (iii) the arc current; (iv) plasma confinement; (v) electromagnetic pumping owing to constrictions in the arc column, resulting in induced gas entrainment; and (vi) magnetic influences (transverse magnetic fields move the plasma in the $\boldsymbol{j} \times \boldsymbol{B}$ direction, while axial magnetic fields tend to induce helical instabilities in the plasma).

With the knowledge available, one can estimate the influences listed under (i)–(v). However, estimation of these parametric influences depends upon the boundary conditions in the neighbourhood of the electrodes. The influence of magnetic fields on the behaviour of both the plasma column and the electrode roots is known only qualitatively and quantitative estimates are extremely difficult to make.

In an arc column dominated by convection, plasma generation is determined by the amount of gas entrained into the column. When the radial entrainment of cold gas into the arc column is very small, the arc column at high currents in a tubular confinement is determined primarily by radiation and is approximately cylindrical. In a cylindrical arc column, the electrical power input into the column is radially diffused by radiation and thermal conduction to the wall of the confining tube.

The electrodes of an electric arc are essential to provide an interface between the plasma and the external electrical circuit for the passage of the electric current. In a non-consumable plasma processing system, maintaining the integrity of the electrodes is of paramount importance, because both the quality and the cost of the process may depend upon the physical conditions of the electrodes. Plasma processing systems often use cathodes made from thermionic materials, such as tungsten. When an inert gas is used to shroud the cathode surface, the cathode material chosen should have a high melting point, a low work function and high thermal conductivity to prevent the melting of the cathode (Ushio 1988).

If the plasma gas is oxidising, the cathode material tends to oxidise, resulting in damage to the cathode. In recent times, hafnium has been used as a cathode material in air or oxygen. At this stage of technological development, plasma currents are limited to $\sim$400 A for hafnium cathodes.

The erosion of electrodes is important in consumable electrode and transferred arc systems. For example, the rate of erosion of the consumable wire in welding is dictated by the welding process requirements.

4. Technology Development

The electric arc is a very interesting and unique phenomenon whose characteristics are not fully understood. The development of plasma technology involving the application of science and engineering to produce an end process or product, can be viewed under the three headings: plasma–material interaction, plasma–electrode interaction, and plasma generation and control. The phenomenon, while providing certain advantages, poses some constraints in technology development. In this section, a few critical constraints posed by the phenomenon and possible solutions for a very limited number of cases are described.

In particular, the technological challenges addressed in this paper are:

- enhanced interaction of material with plasma;
- control of the location of electrode roots;
- control of plasma power.

4·1 Plasma–Material Interaction

Material processing using thermal plasmas may involve the following: melting of material, imparting of momentum to the material, and/or induction of required chemical reactions. Whatever the requirement may be, one crucial technological challenge is to obtain the best possible interaction between the plasma and the material being processed.

When a non-transferred plasma system (Fig. 2*c*) is used, the material is mixed with the plasma, which is generated within a plasma torch or plasma generator. If one assumes an effective mixing of the material with the plasma, then the final temperature of the plasma/material mixture is determined by the enthalpy of the mixture, provided that equilibrium conditions prevail. Owing to the heat transfer or reaction rates involved in the process, equilibrium conditions are hardly ever reached. In most of the industrial applications, the processes are determined by the kinetics of the process and hence equilibrium conditions can be taken to give an upper bound or asymptotic condition.

In plasma spraying, solid material in the form of a powder, with a particle size of 20–100 μm, is injected into a plasma, generated by a non-transferred system as shown in Fig. 2*c*. The material is transported by means of a carrier gas and dispersed within the plasma. For spraying, the particles need to be melted and given sufficient momentum by the plasma jet. Despite the long history of technological development of plasma spraying (approximately 30 years), the thermal efficiency of heating and melting particles in a plasma remains at a low value of 5% (Borbeck and Nicoll 1988).

In non-transferred and in-flight processing systems of the type shown in Fig. 2*c*, the plasma generation part of the system is physically decoupled from the material processing part. The main demand on the plasma generation subsystem is to produce a plasma with the required total enthalpy and spatial profiles of temperature and, sometimes, plasma velocity. The requirement on the material processing part is to ensure that the material to be processed is suitably dispersed within the plasma to obtain adequate mixing, in order to optimise the energy transfer between the material and plasma. It has been found in practice that an effective dispersion of material into a plasma has been a problem, as evidenced in the plasma spraying case.

One way to overcome the limitations of non-transferred and in-flight systems is to inject material directly into the arc column. When material is injected into the current-carrying channel of an arc column, then the Joule heating in the plasma provides additional energy to give higher mixture temperatures than those obtained in non-transferred systems. Although equilibrium conditions may not be reached even in this case, the energy utilisation in processing is likely to be higher because the material is injected directly into the Joule heating region of the arc column. In this case, however, the arcing phenomenon is directly coupled with material processing and control of the process is crucial to obtain the required process characteristics.

The very nature of a narrow arc column, despite its advantages in some applications, introduces a few constraints in the loading of material into the plasma column for the processing of materials. There are two inherent problems encountered in the injection of material into a narrow plasma column: (i) dispersion of material into the plasma column so as to maximise the plasma–

material interaction, and (ii) maintaining the stability of the arc column when one attempts to load material into the discharge column.

A high-enthalpy plasma column, whether current carrying or not, is often a narrow jet of hot gas. In order to disperse material evenly into this jet, one needs to mix a jet of material with the plasma jet. Solid material is usually injected radially into the plasma jet with the use of a carrier gas, in which case the momentum of the carrier gas jet should be sufficient to overcome the shear layer near the plasma boundary. It is also necessary that the momentum of the carrier gas jet is not so large that it penetrates the entire cross-section of the plasma jet and leaves the plasma. Entrainment of the particle-laden jet into the plasma jet requires close control of the carrier gas flow and the amount of material carried by the carrier gas.

When the material to be processed is a liquid, the liquid needs to be atomised and injected into the plasma with a carrier gas. Again, one faces the problem of non-uniform entrainment of the atomised liquid into the plasma. Injection of gaseous material into the plasma appears easier than injecting solid particles or atomised liquid. Experience with the loading of material into a plasma jet reveals that most of the current methods do not disperse the material within a plasma jet in a manner that effectively utilises the plasma enthalpy.

The electrothermal instability of an arc column presents difficulties when one attempts to load material in the current-carrying region. When a cooler material is injected into a region of an arc column, the temperature in that region falls. Since the electrical conductivity is a strong function of temperature, the electrical conductivity in the region where the material is loaded falls and hence the current carried by the region drops. That is, the arc column moves away from the cooler material when the rate of material loading increases above a certain limit.

Several methods have been devised that attempt, with limited success, to overcome the limitation in dispersing material into an electric arc column, while maintaining the stability of the discharge. Most of these methods have relied upon the idea of increasing the volume covered by the discharge, either by a movement of the arc column in space or by creating multiple arc discharges in a given volume (Harry and Knight 1985). For example, in the Tetronics transferred arc system (Cowx and Heanley 1985), the cathode of the discharge is mechanically rotated to generate an arc describing a cone in space. Solid material in the form of powder is dropped into the furnace, with the particles falling through the conical surface of the plasma. In another system (the Ion-Arc plasma system), the discharge is initiated between one cathode and three anodes with their tips placed at 120° around the periphery of a circle below the cathode. The total arc current is shared between the anodes to create effectively three arc columns merging in the inter-anode space to create a large volume of plasma.

One method to improve the efficiency of the plasma–material interaction is to inject the material to be processed in the axial direction of a plasma. One such system, developed for plasma spraying, is shown in Fig. 9, in which the material is injected though the axis of a torch having three cathodes and an anode nozzle (Yen *et al.* 1985; Maruo *et al.* 1988). The acceptability of this system for industrial use remains to be seen. Fig. 10 shows another type of torch which allows the axial injection of material through the arc. This reactor (the Tiddalik arc reactor, Ramakrishnan *et al.* 1989) stabilises the arc by strong vortex gas flows, when liquid material is injected axially. The electrode roots are spun over the electrode surface by the use of a magnetic field. The Tiddalik arc reactor has been operated at the CSIRO laboratories at a power level of 150 kW in argon and an alcohol injection rate of approximately 40 L hr^{-1}.

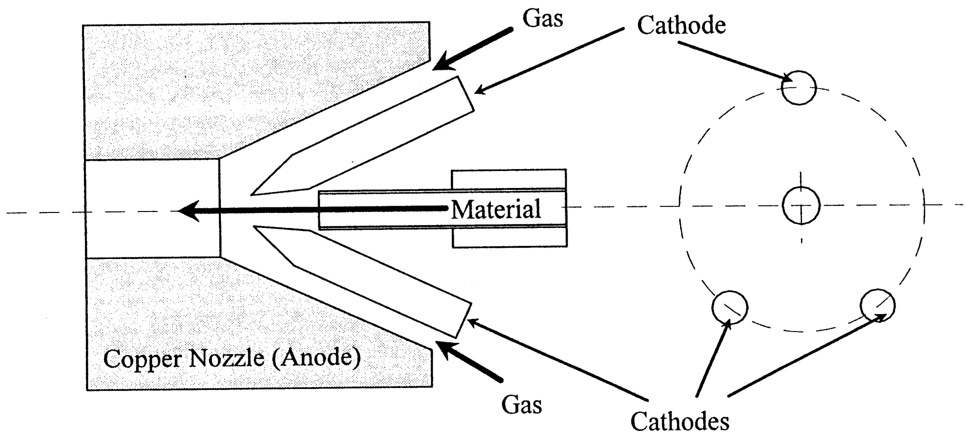

Fig. 9. Plasma torch with three cathodes for axial material injection.

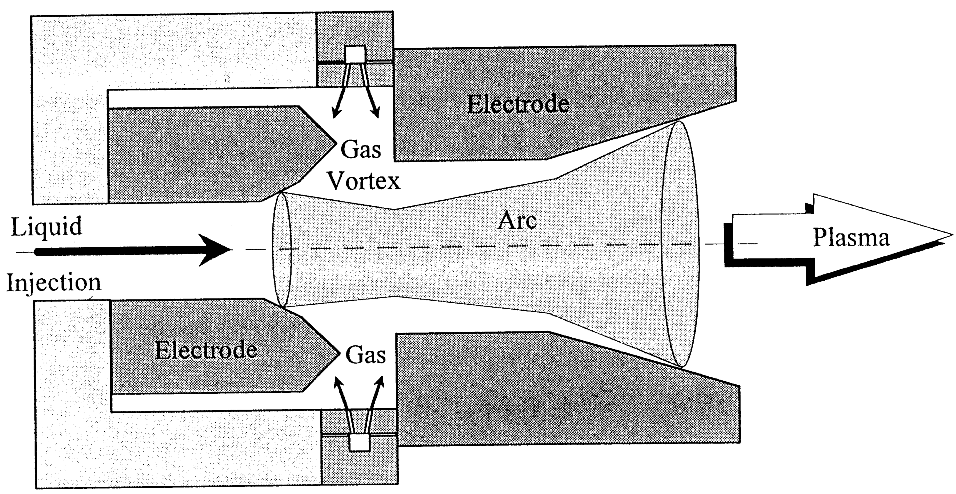

Fig. 10. The Tiddalik plasma reactor for axial injection of material.

4·2 Plasma–Electrode Interaction

The electrodes of an arc discharge provide a means to connect electrically the discharge to an external power source. If one or both of the electrodes are consumable, then the rate of consumption of the electrode(s) is important from the point of view of replenishing the electrodes to make the process continuous. For example, in gas–metal arc welding (GMAW) or twin arc wire spraying, shown in Fig. 2*d*, the electrodes are consumable wires, which have to be fed at a determined rate. In plasma systems, maintaining the integrity of the electrodes is essential because the electrodes of the discharge are expected to be non-consumable. Long electrode lifetimes of typically 100 hours or more are crucial to avoid system outages for maintenance. Cooling of the electrodes in non-consumable systems is necessary to maintain electrode integrity. When consumable electrodes are used, a knowledge of heat flux at the electrodes is needed to determine the rate of consumption of electrodes. Many quantitative scientific studies have been conducted with limited success to estimate the heat fluxes at electrodes.

The polarity of the electrodes used in an arc system is sometimes important for the successful operation of a process. In tungsten inert gas (TIG) welding, the cathode is made of tungsten, with argon as the shield gas, and the anode is the workpiece where most of the heat is liberated (Ghent and Kerr 1980). In GMAW, the consumable wire is the anode and the workpiece is the cathode. This polarity in GMAW is needed to obtain controlled melting of the consumable wire.

One of the crucial design issues faced by developers of arc and thermal plasma systems is to have some idea of where the electrode root is likely to be located in the plasma device, particularly in a novel system. If the location of the electrode roots cannot be determined *a priori*, control of the electrode temperature or its consumption becomes well nigh impossible.

In GMAW, the location of the electrode root on the welding wire needs to be at the tip of the wire, rather than wandering over the exposed surface of the wire. Further, the electrode attachment should be such that the liquid metal droplet at the end of the wire is engulfed by the anode attachment in order to propel the droplet towards the weld pool. If the electrode attachment takes place at the bottom of the metal droplet (Lancaster 1980), the reaction forces of the electrode jet due to electromagnetic pumping repel the droplet away from the weld pool.

A conventional plasma torch is shown in Fig. 11. In such a torch, the cathode is made from a thermionically emitting material, while the anode of the discharge is the nozzle of the torch. While the cathode location is fairly well known and controlled, the exact location of the anode root on the nozzle wall is unknown. Since the location of the anode root is not known, the length of the discharge is not known and hence the total enthalpy of the plasma generated by the torch and the electrical parameters of the discharge cannot be computed, although extensive knowledge of the behaviour of arc columns in convective flows is available. This aspect makes the design of plasma torches very difficult.

Recent studies have shown that the anode root in a conventional plasma torch moves back and forth on the wall of the nozzle at a frequency of a few kHz (Fincke 1992; Coudert *et al.* 1993). In plasma spraying, such oscillations induce fluid dynamic fluctuations in the plasma plume emanating from the torch, and these fluctuations are believed to affect the melting of the particles to be sprayed, resulting in unmelted particles in the coating.

The reason for the oscillation of the anode root over the nozzle wall is not known. One plausible explanation is that when the anode root is located near

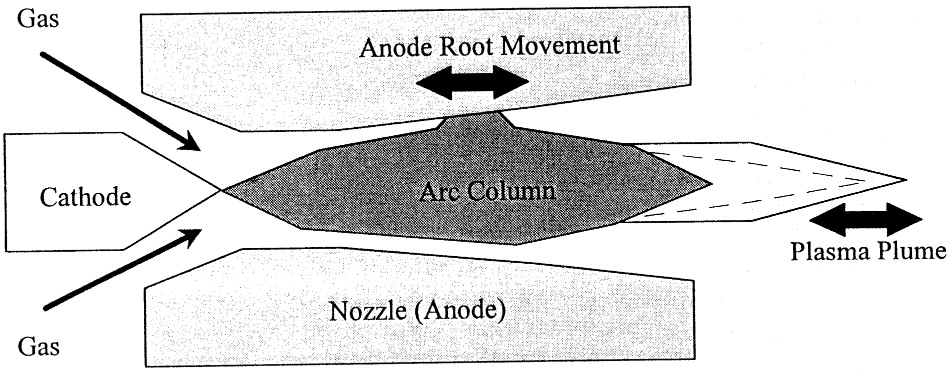

Fig. 11. Conventional plasma torch.

the upstream end of the nozzle, the gas flow tends to sweep the anode root downstream, thus extending the length of the arc column. At one stage during this extension of the arc column, an electrical breakdown occurs near the upstream region to shunt the extended arc column. Thus, the arc length becomes small, and the cycle repeats. The fluctuations in the length of the arc column are reflected in the total arc voltage. It has been found that when a molecular gas, such as nitrogen or hydrogen, is used as the plasma gas, the fluctuations in the amplitude of the arc voltage are very strong. These fluctuations not only disturb the stability of the plasma generated, but also create problems for the electrical power-conditioning apparatus. Experience also shows that when the plasma gas is argon, the voltage trace is generally smooth, indicating that an arc in argon is stable.

In pulsed GMAW, the required attachment of the anode root on the metal droplet at the end of the welding wire and the heat flux to the wire (Hiltunen 1980) are obtained by a choice of a suitable combination of argon and carbon dioxide as the welding gas.

4·3 Plasma Generation and Control

Plasma generation and control, in the context of technology development, involve obtaining the desired operation of a process through appropriate equipment design. For system development, one should take into account the requirements of the plasma–material and plasma–electrode interactions as dictated by the process under development and provide a means for the realisation of the process.

The development of plasma systems involves the following: (i) the generation of a plasma (either generated in a non-transferred plasma generator or an arc column) of suitable gas composition at the required temperature, gas flow rate and total enthalpy or power level; and (ii) the control of the plasma–electrode interface to maintain the required electrode conditions (prevention of melting of electrodes in plasma torches or achieving the required melting characteristics when the electrodes are consumed in the process).

The control of the electrode roots of an electric arc involves: (i) controlling the heat load on the electrode surface by control of the root attachment; (ii) controlling the nature of the arc attachment (constricted or diffuse); and (iii) controlling the location of the electrode roots. Studies conducted so far have provided only very limited knowledge to assist the above requirements.

Plasma generation is the basis for all plasma applications. In this section, a few issues related to the control of the plasma generated in a plasma torch are addressed. The issues driving technology developments addressed here are: (i) enthalpy scaling, (ii) control of electrode roots, and (iii) control of plasma power.

Plasma torches are used in a number of applications and the electrical power rating of industrial torches may vary from 10 kW to a few MW. Non-transferred plasma torches of 10–100 kW power rating are used in plasma spraying, while higher power levels are employed for bulk material processing, including furnace heating.

As mentioned in Section 3·1·2, the total enthalpy of the plasma gas leaving a plasma torch is

$$\int_0^R \rho u_z h \, 2\pi r \, \mathrm{d}r = VI - \text{losses}\,, \tag{8}$$

where the electrical power input into the plasma is the product of the arc voltage V and arc current I. The losses from the plasma are the heat transported to the electrodes and nozzle walls by thermal conduction and radiation. This amount of heat is carried away by the coolant used to cool the electrodes and the nozzle of the plasma torch. The thermal efficiency of plasma generation by plasma torches varies between 50 and 70%, the lower values being typical for small torches of power levels up to 100 kW.

The term on the left-hand side of equation (8) depends upon the total mass flow rate of hot plasma and the temperature of the gas at the exit of the plasma torch. When the plasma temperature needs to be higher (>10,000 K), the plasma jet needs to be constricted with the required amount of gas carried within the jet. Plasma torches rated at an electrical power level of up to 150 kW deliver high-enthalpy plasmas. In these torches, inert gases and/or mixtures of inert gas and molecular gases are used. Further, torches for use at lower power levels have the configuration of a convential plasma torch, shown in Fig. 11, with a rod-type cathode and a nozzle anode.

Plasma torches (Camacho 1988) rated at power levels in excess of 250 kW are used in bulk material processing or furnace heating. At high power levels, the cost of using inert gases becomes excessive and most of the industrial torches use air, a molecular gas such as nitrogen or hydrogen, or a gas which can be used in the process. When air is used as the plasma gas, thermionic cathodes cannot be used because of oxidation. Hence copper is used as the cathode and anode material. In this case, the electrode roots are rotated (Fig. 12) over the circular surface of the electrode by means of a magnetic field. The required distribution of heat load over the surface of the electrode necessitates the use of larger diameter (~100 mm) nozzles and electrodes. Hence the plasmas produced by high-power plasma torches have medium enthalpies, the exit temperature of the plasma being ~3000 K.

From equation (8), it can be seen that obtaining higher powers requires an increase in the arc current I or the arc voltage V. Increasing the arc current above 1 kA often results in serious cathode erosion when thermionic cathodes are used. When a non-thermionic cathode is employed, the cathode root needs to be rotated over the cathode surface. When the arc current is increased, one needs a larger cathode surface to distribute the heat load and prevent electrode melting. A larger cathode surface requires a larger diameter electrode and nozzle, and hence produces lower exit temperatures.

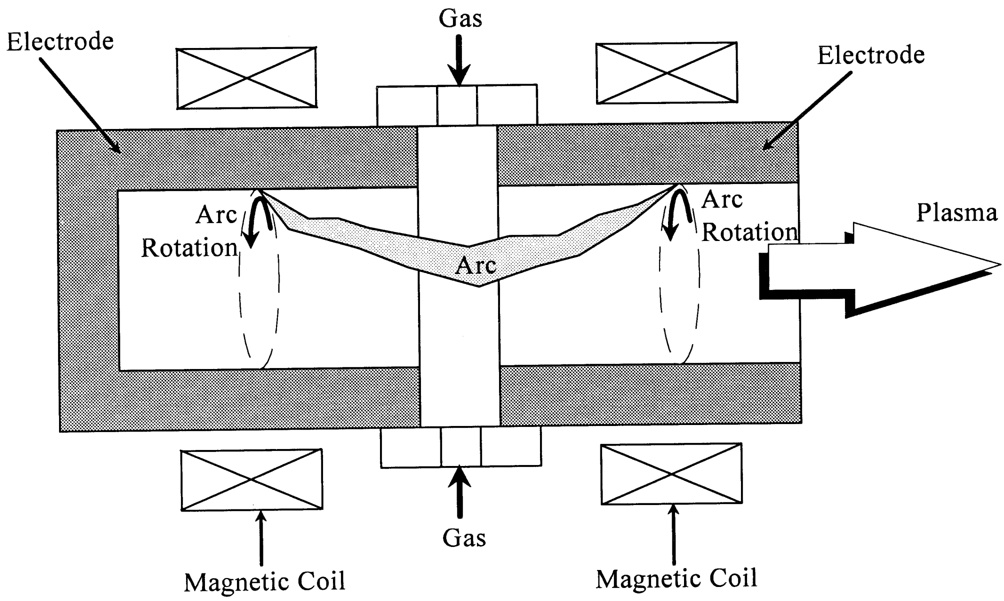

Fig. 12. High-power, medium-enthalpy plasma torch.

The arc voltage depends upon the length of the arc column. When the arc length becomes large, the losses from the arc column increase. As mentioned in Section 3·1·2, in the downstream region of an arc column, radial entrainment of gas into the plasma column is small. The column in the downstream region is cylindrical and dominated by losses. Hence increasing the arc length beyond a certain level is likely to lead to poor thermal efficiencies. In industrial plasma torches, the highest arc voltage used is a few kV (Muller 1987; Muller *et al.* 1987).

One way to improve plasma generation in the downstream region of the arc column is to force radial entrainment of gas into the arc column in the downstream regions. This idea has been implemented in what are known as transpiration-cooled arcs.

In a non-transferred plasma torch, the design and development of equipment requires a knowledge of the location of electrode roots for the following reasons: (i) the voltage of the arc column and hence the power level of the arc is determined by the length of the arc, which depends upon the position of the electrode roots; (ii) controlling the temperature of the electrode by cooling and distributing the heat load at the arc attachment is essential to maintain the integrity of the electrode; and (iii) maintaining the stability of the plasma may be necessary for stable plasma generation.

In a convential plasma torch (Fig. 11), the nozzle acts as the anode of the discharge. The nozzle, being made of high-conductivity copper, presents an equipotential surface for the anode root attachment to take place over the whole length of the nozzle. Similar situations arise when the cathode of the arc is also made of copper, as in the case of high-power, medium-enthalpy plasma torches.

If the nozzle wall is not an equipotential surface, then there is little opportunity for the anode root to wander over the nozzle wall. The nozzle can be made up of a number segments, with each segment insulated from the adjacent ones to provide a fixed anode segment for anode root attachment, as shown in Fig. 13. Such a cascade arrangement has been used in a number of studies to produce a cylindrical arc column. Similar arrangements have also been used in large medium-enthalpy plasma torches to produce an arc of sufficient length and voltage to meet required power levels. Such torches, in which the anode root is allowed to wander over only a fraction of the total length of the nozzle, are known as fixed-length plasma torches (Hayashi *et al.* 1987).

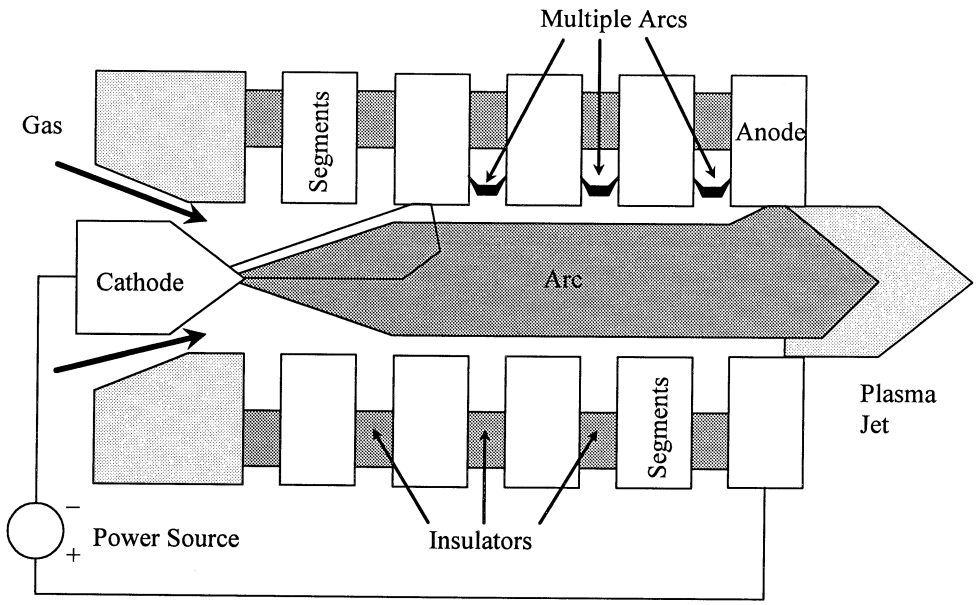

Fig. 13. Torch with segmented/cascade nozzle for fixed-length arc operation.

The problem one faces in the design of a cascaded or segmented nozzle is to maintain the stability of the arc without multiple arcing (Fig. 13). The ratio of the width of each segment to the width of the insulator must be maintained at an appropriate level so that no electrical breakdown is possible between adjacent segments. Multiple arcing often leads to catastrophic failure of a plasma torch because of the damage caused to the segments of the nozzle by arcing. Multiple or double arcing is also a serious problem in transferred arc systems used for plasma cutting and material processing.

A simple design criterion for segmented torches to avoid double arcing is to ensure that the voltage between adjacent segments is less than that required to maintain an arc between the two segments. Another solution would be to create a cool boundary layer along the surface of the nozzle to prevent the formation of arcs between segments. However, breakdown mechanisms between metallic parts of a plasma system are not clearly understood and no design parameters are available.

In many industrial applications, the total enthalpy of the plasma generated by a plasma torch needs to be controlled to meet process requirements. The parameters which can be varied to control the total enthalpy are (i) gas composition, (ii) gas flow rate, (iii) arc current, and (iv) arc length.

If the plasma torch operates in single gas mode, the composition of the plasma gas cannot be varied. However, when gas mixtures are used, the power level of the torch can be controlled by varying the amount of molecular gas in the composition, because molecular gases tend to give higher arc voltages. For example, in plasma spraying a mixture of argon and hydrogen is used and the power level of the torch can be varied by controlling the proportion of hydrogen. For a typical plasma spray torch operating in argon at a flow rate of 50 $\mathrm{L\,min^{-1}}$ and a current of 500 A, the power level can be varied from approximately 12 to 50 kW with the addition of 15 $\mathrm{L\,min^{-1}}$ of hydrogen. With the addition of hydrogen, however, the temperature profile of the plasma plume becomes narrower, the electrode life reduces and the plasma plume becomes unstable because of the movement of the anode root over the nozzle wall. Further, the control becomes very sensitive to the amount of hydrogen added to the plasma gas.

In a conventional plasma torch, increasing the gas flow rate increases the plasma power, but this type of control is rather insensitive. When the gas flow rate is increased, the entrainment of cold gas in the growth region of the arc column increases and more plasma is generated. However the downstream region of the arc column is affected only slightly, unless the gas flow rate is increased by a very large amount.

An increase in the arc current results in an almost linear increase in arc power. However, all the electrical power input does not result in the production of high-enthalpy gas because of increased losses. With an increase in arc current, the diameter of the arc column increases and consequently the arc column tends to 'fill' the nozzle, resulting in greater diffusion of heat to the nozzle wall. Any further increase in arc current above the 'filling' current results mostly in losses.

It is also interesting that in a conventional plasma torch operating in argon (Doolette and Ramakrishnan 1993; Britton 1990), the total enthalpy of the plasma generated is limited because of a limitation in arc voltage attainable owing to the attachment of the anode root near the cathode. Any increase in arc current or gas flow rate does not result in higher values of total gas enthalpy.

Control of the length of the arc at constant current to vary the arc voltage, thereby maintaining a constant arc power, is a method traditionally used in many transferred arc systems. In automated plasma cutting operations, the height of the plasma torch above the workpiece is automatically controlled by a feedback control system to maintain a constant arc voltage.

In non-transferred plasma torches, changing the arc length by means of movable electrodes leads to complex mechanical designs. However, the Advanced Plasma Gun (APG) of Metco (Britton 1990) achieves arc length control by an ingenious design of the cathode assembly used in the torch.

Although designs have been developed to control the total power or the enthalpy generated, there appears to have been little effort made in controlling not only the total power, but also the distribution of power in an arc column. A system incorporating control of the distribution of power in an arc would be valuable for controlled processing of materials injected into the arc column.

Fig. 14 shows the Electronic Plasma Torch developed by CSIRO, which allows control of both the total enthalpy and the distribution of power along the length of an arc column. It can be seen from Fig. 14 that the torch employs a segmented nozzle construction, but each segment can be used as an anode. By the use of high-current solid-state switches, it is possible to sweep the arc along the anodes at any desired frequency of up to 10 kHz. By changing the rate at which the anode root is swept, a spatially modulated plasma can be generated. The EPT, in its simplest form, has been used for plasma spraying (Doolette *et al.* 1989) to yield the following advantages: (i) single gas (argon) operation to obtain a maximum power level of 60 kW, (ii) longer electrode life, and (iii) increased powder deposition efficiency. Further developments of this torch are necessary to realise its full potential in material processing applications.

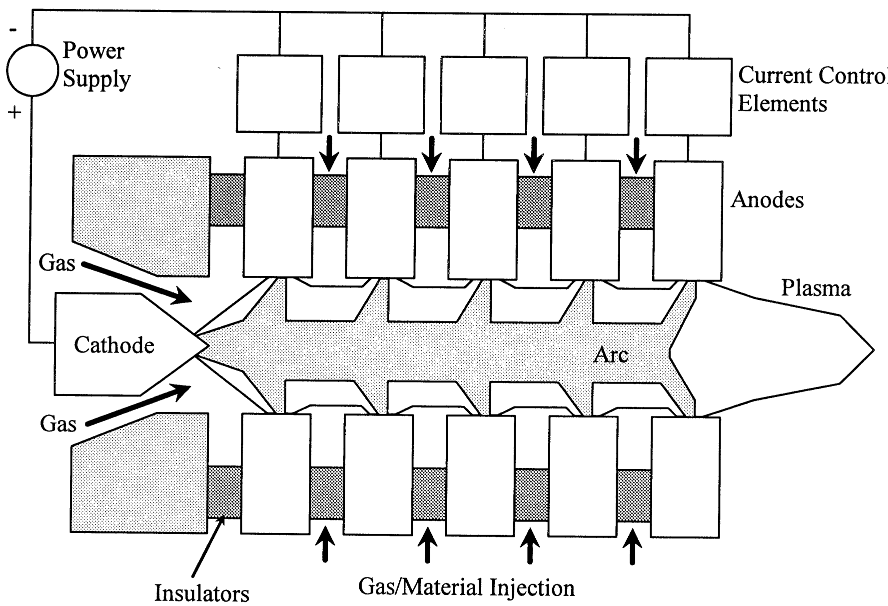

Fig. 14. Electronic plasma torch with multiple anodes for power control.

5. Conclusion

It has been shown that an arc column assumes a narrow cross-section with a high temperature of ~10,000 K because of a large increase in the electrical conductivity of the plasma with temperature. This inherent electrothermal instability makes the current-carrying or heat-generating region of the plasma move away from the cooler material injected into the plasma.

The generation of plasma involves the heating of a gas of suitable composition by forcing gas entrainment into an arc column. Larger entrainment of cooler gas into an arc column results in a greater amount of plasma generation. When very little gas is entrained, the heat generated in the plasma is lost to the surroundings.

Studies conducted so far on the attachment of the arc to electrodes provide some guidance for the estimation of heat fluxes at the electrodes. However, the nature and location of electrode attachment still remains to be explained.

The application of thermal plasmas in industry has utilised the phenomenal characteristics of narrow column and high temperature to significant advantages in plasma cutting, plasma spraying and plasma welding. However, the narrowing of the arc column at high temperature presents difficulties for the injection of material into the plasma for material processing.

The industrial requirements for technology development are to enhance the utilisation of the plasma properties and to provide a greater control of the process. Future developments of plasma technology need to consider issues related to the plasma–material and plasma–electrode interactions, and plasma generation and control in the light of industrial requirements. A few innovative solutions for the axial injection of material into the plasma, the control of electrode-root positioning and the control of energy distribution in the plasma have been discussed.

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